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Brief Report

Developing Concrete Using +80 wt% of Copper Tailings and Slag in Chile: Insights into Sustainable Waste Material Utilization

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Abstract

This study addresses the ongoing challenge of mitigating the environmental risks posed by metal tailings storage facilities while simultaneously offering a novel and sustainable alternative to conventional construction materials. This study examined the utility of copper tailings and slag, two main byproducts of the mining industry, through the formulation of concrete that incorporates over 80% of these materials by weight. Comprehensive physical, chemical, and mineralogical analyses were performed following the Chilean and international standards. These assessments confirmed the presence of potentially hazardous elements and demonstrated the effectiveness of passivation treatments that make these materials suitable for reuse. Three experimental concrete mixtures were designed and tested under optimum laboratory conditions. The results showed that the compressive strengths exceeded 25 MPa within 7 days, whereas conventional concrete typically requires 28 days to achieve a comparable performance. The mixes also demonstrated effective immobilization of acidic and metallic components, ensuring compliance with the Chilean national regulations governing aggregates and construction materials. An economic evaluation highlighted the strong competitiveness of this approach. Production costs decreased by approximately 74% compared to traditional Portland cement concrete, primarily because of the lower raw material costs of tailings and slag. This research presents a technically feasible, economically viable, and environmentally beneficial solution that supports circular economy models in Chile, thereby providing a replicable framework for international applications.

Keywords: copper tailings; slag aggregates; sustainable concrete; circular economy

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1. Introduction

The mining industries process vast quantities of rock globally. The copper production in 2024 reached approximately 22.9 million tons worldwide [1]. Given that copper ore, such as that found in porphyry copper deposits, typically contains an average grade of 0.7% copper, the total volume of processed rock stands at approximately 3300 million tons

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annually. Nearly all of this rock material is deposited in tailings storage facilities (TSFs), which consist of residual waste following the extraction of target minerals from crushed and ground ores [2]. In many mining jurisdictions, the term "pond" does not adequately define the magnitude or environmental significance of these waste repositories [3]. Many TSFs are substantial in scale and often resemble artificial lakes, rather than conventional ponds. For example, as of 2024, the Talabre TSF in Chuquicamata, Chile, spans a perimeter exceeding 52 km. Additional data on these facilities can be obtained from the Chilean National Geological and Mining Service (Sernageomin) [4].

Extensive research conducted between 1970 and 1999 demonstrated that mining-derived contaminants adversely affected both human populations and ecosystems. Studies have documented trace metal contamination in indigenous territories of Brazil [5,6], and the transfer of metals into the human food chain via livestock and soil pollution [7,8]. While corporate negligence is common in the extractive industry, particularly when environmental concerns conflict with profitability, the magnitude of the sector's economic activity complicates regulatory and mitigation efforts. In Europe alone, the mining industry comprises over 17,500 firms, employs approximately 500,000 individuals, and generates an estimated annual turnover of €200 billion [2,9]. The environmental implications of mining are undeniably global, with severe cases of pollution reported in regions such as Bengal [10], Taiwan [11], Brazil, and England [12,13]. These findings highlight a clear historical pattern: mining operations have consistently caused large-scale environmental degradation, with profound and often unquantified impacts on human health. Although the full extent of the morbidity and mortality attributable to mining pollution remains poorly documented, existing evidence underscores the urgent need for stricter oversight and sustainable practices in the industry. Currently, studies on the impact of mining operations are ongoing. For example, in the Mufulira River, mine tailings led to an increased SO_4^{-2} concentration (1396 mg/L), dissolved Al (2115 μg/L), Co (909 μg/L), Cu (7405 μg/L), Ni (51.5 μg/L), Pb (161 μg/L), and Zn (346 μg/L), and a greatly reduced pH (2.04) [14].

Tailing ponds represent one of the most critical long-term environmental challenges faced by the mining industry. These vast reservoirs of finely ground rock, water, and residual processing chemicals (byproducts of ore extraction) pose significant environmental risks that persist even after mining activities cease [15,16]. A major concern is their potential for widespread contamination. Tailings often harbor harmful substances, including heavy metals, arsenic, and sulfide minerals, which can leach into the surrounding soil and groundwater. This leaching process can lead to persistent ecological degradation, posing serious health hazards to nearby communities [15,16].

Despite the challenges, including catastrophic dam failures [17], growing attention is being driven toward developing sustainable tailings and slag management strategies. Among these developments, thickened tailings disposal (TTD) has emerged as a promising and viable approach, with successful implementations in Chile and Peru. TTD offers multiple advantages including improved water recovery, reduced spatial requirements, and enhanced geotechnical stability [3,18]. Although this method represents a significant operational advancement, it fails to address the core issue of material valorization, leaving billions of cubic meters of solid tailings unusable. In copper processing, tailings typically exhibit a complex mineralogical composition dominated by silicon, iron, sulfur, and aluminum oxides [19], with quartz and sericite frequently occurring as major gangue minerals [20]. These deposits often contain economically recoverable residual metals such as copper, molybdenum, and titanium as well as potentially hazardous elements such as arsenic, zinc, and lead [20]. The geochemical pattern of tailings varies significantly depending on their origin and processing history. Some demonstrate natural neutralization capacity owing to the presence of carbonate minerals such as dolomite and calcite [21],

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while others pose pronounced environmental risks through acid rock drainage and metal leaching [22]. The effective management of tailings requires a holistic mineralogical and geochemical characterization to achieve two critical objectives: environmental risk mitigation and resource recovery potential. Robust characterization enables the prediction of long-term geochemical stability, development of targeted remediation strategies, and evaluation of tailings for potential reuse as secondary raw materials. This dual strategy of hazard reduction and value extraction represents a crucial pathway toward attaining sustainable mining practices [21,22].

Some projects have focused on reprocessing tailings to recover residual minerals, thereby reducing their volume and toxicity [23]. Others, like those involving geopolymers, stabilize tailings into solid, inert materials, finding applicability as building materials or paving stones, among other uses [24–27]. Furthermore, computer models are being implemented to determine the strength of materials made from tailing materials [28]. These approaches will transform a long-standing liability into a resource, aligning mining practices with circular economic and environmental goals.

Achieving an optimum strategy for copper tailing deposits and slag management requires addressing at least four critical challenges: (1) the development of formulations capable of immobilizing and neutralizing hazardous elements present in the tailings; (2) the incorporation of a high proportion of tailings material (+80%) into the final product composition; (3) the fabrication of commercially viable products that can generate a profit; and (4) compliance with health, safety, and regulatory standards that permit the safe deployment and widespread use of tailings material products.

The latest regulations and standards in Chile from the "Aggregates for concretes and mortars Requirements" NCh 165, 5th edition, 28 August 2024 ([29], p. 8), state that aggregates form the skeleton of concrete and mortar, forming their largest proportion and directly influencing strength, durability, and elasticity. Traditionally, concrete or mortar manufacturers were implicitly considered responsible for ensuring aggregate quality. However, according to the updated standard, this responsibility is transferred to the aggregate producer, who must guarantee compliance with technical requirements, supporting both quality assurance and the industrialization of aggregate production. Environmental restrictions on riverbed and well extractions have caused shortages, driving the search for alternative aggregates within a circular economic framework. Consequently, the standard incorporates recovered aggregates from fresh or hardened concrete, as well as artificial aggregates from blast furnaces, electric arcs, basic oxygen steel slags, and copper smelting slag. Mixed aggregates from general construction demolition (CDW) are excluded because of insufficient national studies. A validation methodology (sub-clause 7.7) enabled the assessment of new artificial aggregates for use in concrete and mortar. To further research their viability, Annexes I and J were added, which specifically addressed copper tailings as promising artificial aggregates for sustainable, large-scale applications.

In this study, we present a case involving a concrete formulation composed of over 90% copper tailings and slag. The material achieves significant compressive strength within just 7 days of curing and effectively immobilizes both acidic components and heavy metals, restricting them to concentrations well below the thresholds established by the Chilean national standards for materials with concrete-like applications. The estimated cost of this formulation solution is approximately 50% lower than that of the conventional natural aggregates Portland-cement-based formulations. This approach addressed four main challenges: (1) safe formulation (2) enables large-scale utilization of tailings material from deposit sites, as well as slag material; (3) a stable formulation achieving rapid strength development with a significant lower cost than the conventional Portland formulation; and (4) complies with national regulations, as mentioned before, since 2024 Chilean standard

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NCh 163:2024 "Aggregates for Mortars and Concrete—Requirements" permit the use of these products in Chile [29]. Finally, this study demonstrates a cost-effective product capable of competing in concrete and reinforced concrete market in Chile, with the potential for broader international applications.

2. Characterization & Methods

The scope of the tests was extensive. The "NCh" in the following sections is Spanish for "Norma Chilena" or "Chilean Standard" in English. The Chilean standard follows no international norm or standard that is 100% equivalent but has broad overlap with the following international standards:

- ASTM C87, Standard Test Method for Effect Organic Impurities in Fine Aggregates on Strength of Mortar.
- ASTM C123, Standard Test Method for Lightweight Particles in Aggregate.
- ASTM C227-89, Standard Test Method Alkali Reactivity of Cement-Aggregate Combination (MortarBar Method).
- ASTM C1567, Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious and Aggregate (Accelerated Mortar-Bar Method).
- ASTM C1293, Standard Test Method for Determination of Length Change of Concrete due to Alkali Silica Reaction.
- UNE EN 933-9, A European standard. In part 9: Evaluation of fines—Methylene blue test.

Mentioned below are the series of tests carried out:

General Physical Tests

The tests conducted to evaluate the general physical requirements are listed below:

1. Material thickness less than 0.075 mm, according to NCh 1223
2. Sand equivalent, according to NCh 1325 (fine aggregate)
3. Water absorption, according to NCh 1239 (fine aggregate) and NCh 1117 (coarse aggregate)
4. Wear resistance (Machine in Los Angeles, Chile), according to NCh 1369 (coarse aggregate).
5. Form coefficient, according to NCh 3240 (coarse aggregate)
6. Crumbly particles, in accordance with NCh 1327
7. Resistance to disintegration by sulphates, according to NCh 1328
8. Crushing rate, according to Annex C NCh163
9. Crushed particles, according to Annex B NCh163 (coarse aggregate)
10. Light particles, according to ASTM C123
11. Granulometric designation, according to NCh 165
12. Laser granulometry (complementary test, not part of the requirements of NCh 163)

General Chemical Tests

The tests carried out to evaluate the general chemical requirements are presented below:

1. Organic impurities, according to NCh 166 (fine aggregate)
2. Chloride content, according to NCh 1444
3. Sulphate content, according to NCh 1444
4. Methylene blue, according to BS EN 933-9 (a mandatory test for fine aggregates that do not meet requirements 1 and/or 2 of Table 1 of NCh 163, version 2024)

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Table 1. Heavy metals in the tailings sample from the leachate.

ID	Heavy Metal (mg/L)							
	Lead	**Cadmium**	**Mercury**	**Crome**	**Barium**	**Selenium**	**Arsenic**	**Silver**
Tailings	4.86	0.025	<0.019 [1]	2.59	<0.236 [1]	0.83	<0.190 [1]	<0.105 [1]
CMP [2] limit	5	1	0.2	5	100	1	5	5

[1] Value lower than measurable by test. [2] Maximum Allowed Concentration, according to Supreme Decree D.S. 148, Chilean standard.

In this paper, we have not shown complete details of the results and tests carried out, as the scope of this work only involves highlighting the depth and variety of the tests performed. Nevertheless, we have provided sufficient data on the sample material from the tailings ponds and the slag from the foundry, ensuring readers can clearly follow and understand the results.

In the following sections, we discuss the elements present in the tailings pond, the slags used, and the hazardous concentration levels within these samples. All tests on samples were performed by the certified national laboratory IDIEM (Investigación, Desarrollo e Innovación de Estructuras y Materiales) [30]. Full reports along with the online verification codes are included in the Supplementary Section. These reports are in Spanish and were issued by the National Chilean Laboratory.

3. Results and Discussion

3.1. Sample Material

Figure 1 shows an image of the slag and tailings pond material, as received. The sample was dried and kept under standard room temperature (seasonal average indoor temperature in Chile is 17.1 °C to 25.3 °C, in the Santiago area), pressure, and humidity conditions.

Figure 1. Photograph shows a visual registry of the tailings pond material and slag material.

To determine the concentration of heavy metals present in the leachate of the tailings sample, the PLPS Test, indicated in the Chilean regulations in NCh 2746 standard, "Soils and residues—Determination of mobility of organic and inorganic analytes—Synthetic precipitation (rain) leaching procedure," was performed. The results and the maximum allowable limits are presented in Table 1.

Table 1 presents the concentrations of heavy metals found in the leachates of the tailings sample, which is in agreement with the maximum permissible concentrations stipulated in Decree 148 of the Ministry of Health. The results of the chemical characterization using the X-ray fluorescence assay performed on the tailings samples are presented in Table 2.

Table 2. Results of the X-ray fluorescence assay performed on the tailings sample.

Compound	%
SiO_2	58.850
Al_2O_3	15.400
Fe_2O_3	5.218
K_2O	4.320
SO_3	4.010
CaO	2.230
Na_2O	2.190
MgO	1.350
TiO_2	0.460
ZrO_2	0.137
CuO	0.256
SrO	0.181
P_2O_5	0.140
MoO_3	0.111
BaO	0.085
Rb_2O	0.078
MnO	0.052
Cl	0.046
Cr_2O_3	0.032
NiO	0.022
ZnO	0.021
V_2O_5	0.015
LOI [1]	4.6

[1] Loss on ignition.

From the results presented in Table 2, it can be inferenced that the tailings were mainly composed of silica oxide, aluminum oxide, and iron oxide, which represent approximately 79% of the material.

The crystalline phases of the materials were also determined using the X-ray diffraction technique; this data is shown in Table 3. The three main crystalline structures in the tailings were quartz, by-townite, and illite, which represented approximately 43% of the material. This indicates that the crystalline phases in the tailings varied and were not concentrated in a few minerals.

Table 3. X-ray diffraction test results of the tailings sample.

Crystalline Phase	Formula	Weight Percentage Rietveld Method [%]
Quartz	SiO_2	21.40
Bytownite	$(Ca,Na)(Si,Al)_4O_8$	11.90
Illite	$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$	10.17
Orthoclase	$KAlSi_3O_8$	9.08
Albite	$NaAlSi_3O_8$	8.25
Oligoclase	$(Na,Ca)(Si,Al)_4O_8$	7.81
Anorthite	$CaAl_2Si_2O_8$	6.03
Muscovite	$KAl_2(Si_3Al)O_{10}(OH,F)_2$	5.29
Chamosite	$(Fe^{2+},Mg,Fe^{3+})_5Al(Si_3Al)O_{10}(OH,O)_8$	4.30
Biotite	$K(Mg,Fe^{2+})_3[AlSi_3O_{10}(OH,F)_2$	3.46
Alunite	$KAl_3(SO_4)_2(OH)_6$	2.70

Table 3. *Cont.*

Crystalline Phase	Formula	Weight Percentage Rietveld Method [%]
Gypsum	$CaSO_4 \cdot 2(H_2O)$	2.50
Sanidine	$(K,Na)(Si,Al)_4O_8$	1.87
Chlorite	$(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2 \cdot (Mg,Fe)_3(OH)_6$	1.79
Labradorite	$(Ca,Na)(Si,Al)_4O_8$	1.54
Phlogopite	$KMg_3(Si_3Al)O_{10}(F,OH)_2$	1.02
Anorthoclase	$(Na,K)AlSi_3O_8$	0.91

Finally, to supplement the traditional granulometry, a laser technique was used to determine the distribution of finer particles in the tailings (below 0.075 mm). The results are shown in Figure 2.

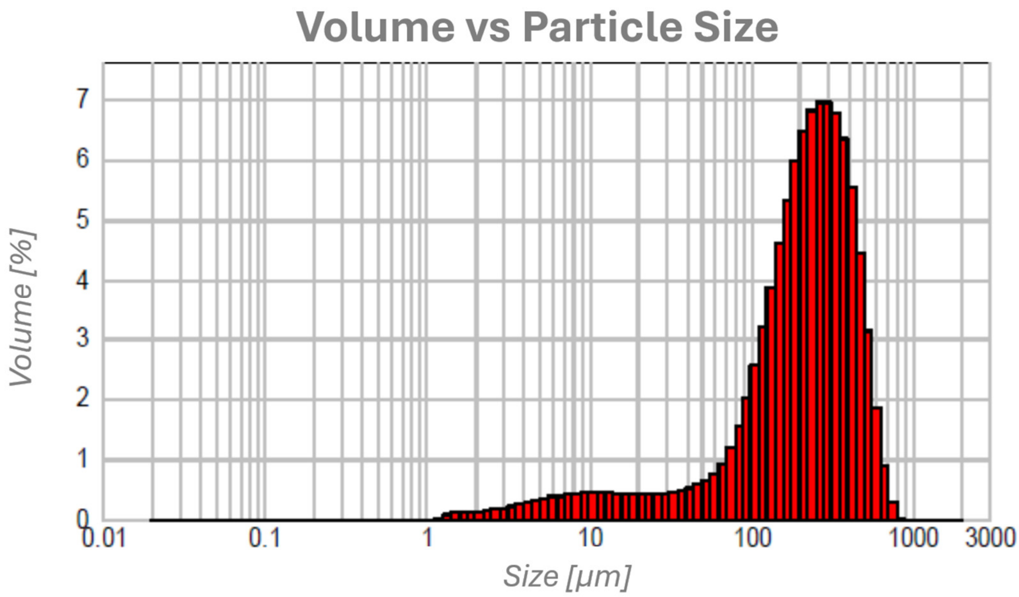

Figure 2. Distribution of particle size of the tailings obtained by laser technique.

In general, the results of the chemical tests complied with the limits indicated in the NCh 163 standard, except for the sulfate content of the tailings, as shown in Table 4. The table shows three different tests: A, B, and C. In test A, two procedures were applied to screen for organic impurities. Test B shows chloride concentration in the sample. Notably, prestressed concretes and special applications may require other criteria established in their respective regulations. In test C, the results clearly indicated the value of sulfates to be above the permissible limit. The methodology used was the addition of lime (calcium hydroxide) to form calcium sulfate, which is separated by sedimentation.

It should be noted that non-compliance with the requirements of the NCh 163 standard, version 2024, does not preclude the use of aggregates. Section 7.2.2 of the standard established that aggregates can still be used under two conditions: the final combination of aggregates complies with the general physical and chemical requirements (Tables 1 and 2 of the standard); a technical study, including test mixtures, confirms that non-compliance does not negatively affect the concrete or mortar properties. The next step was to render these materials within an admissible range. The water-soluble sulfates were treated, allowing for the development of a new product using this nontoxic and stable hybrid material.

Table 4. General chemical test results for aggregates.

TEST	Requisites	Fine Aggregate Limit Value	Obtained Value	Pass/Not Pass
A	Organic impurities—colorimetric standard solution measured from lightest to darkest	Identical	Lighter	PASS
	Organic impurities—color pattern glass	3.0	1.0	PASS
B	Chlorides such as Cl^-, referring to the total sample	0.05%	0.01%	PASS
C	Water-soluble sulfates, referring to dry aggregate	0.30%	0.6	NOT PASS

3.2. Concrete Using Slag and Tailings

The fabrication protocol for the novel hybrid composite material consisting of +80 wt% passivated slag and tailings entailed a two-stage elaboration process. The initial stage involved chemical passivation of the raw tailings material sourced from a retention pond. Subsequently, the passivated product was used as the primary constituent in the formulation of specialized concrete. Arsenic levels in tailings derived from raw copper mining can range from 0.1 to as much as 25 mg/kg, depending on the mineralogy of the deposit and the extraction processes used. In order to be able to use tailings as synthetic aggregates in construction, it is necessary to avoid the leaching of toxic elements that may pose a risk to people and the environment.

The defined process to eliminate leaching includes the addition of sodium hydroxide for pyrite passivation, which triggers an acid–base neutralization reaction, and iron hydroxide for arsenic adsorption, which allows the absorption of arsenic into iron hydroxide. The reaction of these hydroxides allows the non-leaching of arsenic and sulfuric acid from the treated tailings. The application of these inhibiting agents will vary depending on the state of the tailings, either in their dry state or in wet dispersion.

To evaluate the performance of the concrete that incorporated copper slag and tailings, three different test mixtures were tested in the laboratory, with dosages designed by IDIEM. Cement, copper slag, copper tailings, and arsenic marker additives were provided by the research team, and the remaining materials were provided by IDIEM. These three mixes are listed in Table 5.

Table 5. Details of the produced concrete mixes.

Test Mix	Elaboration Date	Cast Identification
Mix 1. Pattern concrete with processed aggregates of natural origin	16 April 2025	2793
Mix 2. Concrete with slag gravel, slag sand, and tailings sand (mixture with superplasticiser type additive)	16 April 2025	2794
Mix 3. Concrete with slag gravel, slag sand, and tailings sand (mixture with plasticizer type additive–retarder)	29 April 2025	2797

The design requirements for the test mixtures were as follows:

- The compressive strength of concrete was greater than 25 MPa at 28 days, as measured in cylindrical specimens with the dimensions of 15×30 cm^2.
- Workability was determined by the Abrams cone slump of 8 ± 2 cm.

Table 6 presents the compositions of Mixes 1, 2, and 3 together with their respective cement-to-water ratios. Data concerning the dry density and water absorption of the aggregates employed in the mixture designs are not included in Table 6 but are provided in the Supplementary Materials.

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Table 6. Composition of mixes and the origin of the materials. The cement water ratio is also indicated.

	Material	Information/Source of the Material	Theoretical Dosage Dry Aggregate [1000 lts]	Theoretical Dosage Dry Aggregate [50 lts]
MIX 1	Cement [kg]	Melón—Melón Extra	300	15
	Gravel natural [kg]	Melón—Pozo San Bernardo	947	47.4
	Sand Natural [kg]	Melón—Pozo San Bernardo	947	47.4
	Additive [g]	Sika—ViscoCrete GL 1303	900	45
	Free water [lts]	Red potable	168	8.4
	Total water [lts]	Red potable	195	9.7
	Theoretical water/cement ratio		0.56	
MIX 2	Cement [kg]	Melón—Melón Extra	300	15
	Gravel Slag [kg]	Anglo American—Fundicion Chagras	1569	78.5
	Sand Slag [kg]	Anglo American—Fundicion Chagras	338	16.8
	Sand Tailings [kg]	AA Las Tórtolas de Minera Los Bronces	507	25.3
	Additive 1 [g]	Sika—ViscoCrete GL 1303	2100	105
	Additive 2 [g]	Identifier of As (arsenide)	253	12.7
	Free water [lts]	Red potable	168	8.4
	Total water [lts]	Red potable	176	8.8
	Theoretical water/cement ratio		0.56	
MIX 3	Cement [kg]	Melón—Melón Extra	300	15
	Gravel Slag [kg]	Anglo American—Fundicion Chagras	1554	77.8
	Sand Slag [kg]	Anglo American—Fundicion Chagras	335	16.8
	Sand Tailings [kg]	AA Las Tórtolas de Minera Los Bronces	502	25.2
	Additive 1 [g]	Sika—Plastocrete HP450	1650	82.5
	Additive 2 [g]	Identifier of As (arsenide)	251	12.6
	Free water [lts]	Red potable	180	9
	Total water [lts]	Red potable	188	9.4
	Theoretical water/cement ratio		0.6	

The complete dataset, as certified by IDIEM, including both the experimental results and mixture compositions, is provided in the Supplementary Materials. It should be noted that this document was presented in Spanish.

As shown in Table 6, the compositions of the different mixes are presented. Mix 1 contained 83.4 wt% of tailings and slag in the total mixture, including water, whereas Mix 2 comprised 82.9 wt%. If the contribution of additional water was excluded, the proportion of tailings and slag increases to 88.7 wt% for Mix 2 and 88.8 wt% for Mix 3.

3.3. Concrete Physical Properties and Operational Parameters

The physicomechanical properties of the novel concrete formulation must demonstrate performance characteristics comparable to or superior to those of conventional concrete. Furthermore, the operational parameters are critically relevant. For instance, a mixture offering a reduced curing period to achieve an equivalent compressive strength would constitute an interesting solution. To determine these properties, several measurements and tests were performed on fresh and hardened concrete. Each test was governed by the National Chilean Standard, which is detailed below.

Tests on Fresh Concrete

The following tests were performed on each trial mix in its fresh state:

- Workability; NCh 1019, Concrete—Determination of Workability—Abrams Cone Slump Method.

- Unit weight (density); NCh 1564, Concrete—Determination of the Unit Weight of Fresh Concrete.
- Air content; NCh 2184, Concrete and Mortar—Test Method—Determination of Air Content.

Tests on Hardened Concrete

The following mechanical strength tests were performed on each trial mix in its hardened state.

Compressive Strength; NCh 1037, Concrete—Compression Test of Cubic and Cylindrical Specimens.

- 2 cylindrical specimens at 7 days.
- 2 cylindrical specimens at 28 days.
- 1 cylindrical specimen at 60 days.

The values for the effective water–cement ratios, results of the Slump tests, densities of the mixes, and the data on air content is provided in Table 7.

Table 7. Details of the test results obtained from fresh concrete for the three mixtures.

Mix	Effective *w*/*c* Ratio after Workability Adjustments	Abrams Cone Slump [cm]	Apparent Density of Concrete [kg/m^3]	Air Content [%]
Mix N°1: Reference concrete with processed natural aggregates	0.63	8.5	2407	0.8
Mix N°2: Concrete with slag gravel, slag sand, and tailings sand (superplasticizer mix)	0.51	8.5	2981	1.2
Mix N°3: Concrete with slag gravel, slag sand, and tailings sand (plasticizer–retarder mix)	0.6	8.5	2924	1

In the Abrams cone settlement, all mixtures fell within the range of 8 ± 2 cm. Regarding bulk densities of the fresh mixtures, the concrete with incorporated slag exhibited the highest densities: 2981 kg/m^3 for Mix 2 and 2924 kg/m^3 for Mix 3. This represents an increase in density of 23.8% and 21.5%, respectively, compared to the standard mix (Mix 1).

Regarding the air content, no major variations were observed between the mixtures because, in all cases, values close to 1% were obtained. Additionally, 24 h after the test mixtures were prepared, the specimens were visually inspected and were hard to touch and suitable for demolding.

The results of the compressive strength tests for the three test mixtures are presented in Table 8. The results of the 28-day compressive strength tests showed that all mixtures met the minimum target strength of 25 MPa. Given these results, the mixture designs can be optimized by reducing the cement doses while still meeting the target of 25 MPa.

Table 8. Compressive strength test results on cylindrical specimens.

Mix	7-Day Compressive Strength [MPa]	28-Day Compressive Strength [MPa]	60-Day Compressive Strength [MPa]
Mix N°1: Reference concrete with processed natural aggregates	28.3	37.5	42.7
Mix N°2: Concrete with slag gravel, slag sand, and tailings sand (superplasticizer mix)	44.6	55.3	62.2
Mix N°3: Concrete with slag gravel, slag sand, and tailings sand (plasticizer-retarder mix)	37.7	46.9	51.4

It is important to note that the resistance results are not directly comparable because different additives and doses were used; however, the results show interesting and clear trends.

Finally, it is worth noting that compressive strengths of 25 MPa or higher can be obtained using artificial aggregates, such as slag and copper tailings studied (at the dosages indicated in Table 6), without causing setting delays in the mixes.

The results presented in Table 8 are promising. Both Mix 2 and Mix 3 achieved similar or higher compressive strengths as the reference (Mix 1) in only 7 days, whereas Mix 1 required 28 days. Furthermore, on day 7, the compressive strength of Mix 2 was higher than that of regular concrete (Mix 1) on day 60. On day 28, both Mix 2 and Mix 3 exhibited compressive strengths that were higher than those of regular concrete (Mix 1) on day 60.

3.4. Concrete Economical Analysis

The global construction industry faces two major challenges: the relentless demand for affordable building materials and the urgent need to mitigate its significant environmental footprint. Concrete, the world's most consumed material, after water, is at the nexus of this challenge, with the production of ordinary Portland cement and the extraction of natural aggregates contributing substantially to carbon emissions, energy consumption, and natural resource depletion. Concurrently, industrial mining operations generate vast quantities of solid waste, referred to as tailings, which are stored in large impoundments. These repositories represent a significant financial liability for mining companies, a perpetual management concern, and a potential environmental hazard.

In this context, the development of a novel concrete composite incorporating 80% by weight (wt%) of these industrial tailings and slag presents a transformative opportunity for a circular economy model. This approach not only assigns value to a waste stream but also directly displaces the demand for virgin natural aggregates. The potential economic advantages of this substitution are significant, given that the sourced tailing/slag material is estimated to have a cost 80% lower than that of traditional aggregates. This significant reduction in raw material costs forms a compelling hypothesis for enhancing the economic viability.

However, a comprehensive economic analysis must extend beyond material input costs. The integration of a new waste-derived material into a high-performance composite introduces other potential cost factors that must be evaluated rigorously. These include the processes of passivation and pretreatment of the tailings, potential adjustments to the concrete mix design, any implications for workability and curing time that might affect labor and project scheduling, and the long-term durability performance which impacts the lifecycle cost of structures built with this material.

Therefore, this economic analysis seeks to transcend a simplistic comparison of unit costs to provide a holistic assessment of the economic feasibility of tailings-based concrete. It evaluates direct material savings against potential processing and operational costs, models the total cost of production, and discusses broader economic implications, including reduced waste management liabilities, potential for new market creation, and the value of enhanced environmental sustainability. The primary objective was to determine whether an 80% reduction in aggregate material cost translates into a commercially viable and competitive product, thereby validating its potential for large-scale adoption in the construction industry.

3.5. The Chilean Case

The availability of natural aggregates faces increasing legal restrictions, whereas tailings represent a massive and underutilized resource [31]. From a regulatory perspective, the exploitation of natural aggregates requires cumbersome permits, whereas tailings, provided that they are neutralized and comply with environmental regulations, do not present further restrictions [32]. Aggregate extraction generates environmental impacts, such as riverbed degradation and biodiversity loss, whereas the use of tailings contributes to the valorization of liabilities and reduces the risks of leaching, acid drainage, and dispersion of volatile sands [33]. Finally, in terms of sustainability, access to natural aggregates is becoming increasingly complex, while tailings align with the principles of the circular economy, enabling the large-scale reuse of materials historically defined as waste. With the new regulation in place in Chile, this exercise makes sense.

To assess the economic feasibility of incorporating environmental liabilities (slag and tailings) into concrete production, a comparative cost calculation per cubic metre was performed, as shown in Table 9. For the alternative with environmental liabilities, a flat rate of CLP of 10/kg was applied to the total weight of the mix (aggregates, cement, and additives). This result contrasted with the conventional option using natural aggregates at market prices.

Table 9. Comparison of concrete production costs per m^3 (excluding transport).

Concept	Quantity (kg)	Price Natural Aggregates (CLP/kg)	Price Liabilities (CLP/kg)	Cost Natural Aggregates (CLP)	Cost Liabilities (CLP)
Aggregates	2391	18		43,038	26,930
Cement	300	180	10	54,000	0
Additives	2	3000		6000	0
Total mix	2693			103,038	26,930

Note. The calculation for the option with environmental liabilities considers a flat CLP rate of 10/kg applied to the total mix (aggregates + cement + additives). The market values of natural aggregates, cement, and additives correspond to the averages reported in Chile for 2024.

The analysis shows that the option with environmental liabilities (waste) reaches a total cost of CLP 26.930/m^3, whereas the conventional option with natural aggregates amounts to CLP 103.243/m^3. This implies an absolute saving of CLP 76.313/m^3, equivalent to a 74% reduction in the total cost of concrete production.

Economic Sensitivity Analysis

The economic analysis presented in this article is conducted through a first-order, pilot-scale comparative assessment, aimed at identifying the potential cost advantage resulting from the substitution of conventional aggregates with tailings- and slag-based materials under controlled laboratory and pilot-scale conditions. Accordingly, the evaluation assumes a flat unit cost for tailings-based mixtures and does not include transportation logistics costs or extended quality control procedures.

These factors are acknowledged as relevant for large-scale industrial implementation and may influence economic feasibility depending on the characteristics of each mining tailings site and its distance to concrete production facilities. In addition, quality control procedures vary according to material heterogeneity and the performance requirements of the final concrete product.

Nevertheless, a sensitivity analysis indicates that the proposed approach is economically justified in scenarios where tailings are integrated within mining–construction industrial hubs. In such contexts, reduced transport distances and the availability of existing infrastructure enable the decrease in raw material costs and the valorization of an environmental liability to offset the additional operational requirements.

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4. Conclusions

This study presents a feasible pathway for converting copper tailings and slag, from a substantial environmental liability into a valuable resource for the construction sector. The engineered concrete, consisting of more than 80% tailings and slag, effectively immobilizes hazardous elements while attaining compressive strengths above the regulatory thresholds within 7 days. This performance directly addressed critical safety and durability challenges associated with conventional materials. Importantly, this formulation complies with Chile's updated NCh 163:2024 standard, which explicitly supports the incorporation of alternative aggregates. Notably, within 7 days, both alternative mixes (Mixes 2 and 3) reached compressive strength levels that the reference mix (Mix 1) required 28 days to achieve, thereby offering the potential to reduce curing periods in practical construction applications.

The economic assessment indicated that the markedly reduced cost of tailings/slag feedstock, combined with an overall production cost approximately 74% lower than that of conventional concrete, constitutes a strong commercial case. Beyond providing a cost-effective construction material, this approach establishes a scalable circular economic framework that mitigates the substantial waste burden of mining operations. This research makes a significant contribution to resource efficiency, waste reduction, and environmentally responsible construction practices by delivering a profitable, regulatory-compliant, and sustainable solution for tailings and slag valorization.

While the economic analysis demonstrates a significant cost advantage at the pilot scale, the feasibility of industrial implementation remains contingent upon site-specific logistical factors and the internal technical and operational requirements established by mining companies for the use of concrete materials. In this regard, future studies should prioritize comprehensive economic analyses that explicitly incorporate these elements to support large-scale adoption.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18041889/s1, The supplementary material contains details of several of the tests carried out and the methods. These were provided by the certifying laboratories when available.

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